Correlations of Submersible Cable Performance to Neher-McGrath Ampacity Calculations

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Abstract—**The configuration and application of electric submersible pump cable demands careful consideration of temperature effects on the cable materials. Tests were conducted to develop correlation factors and modifications to the Neher-McGrath thermal model. These disclose the unique features of the cable. A series of equations are presented. Application charts are provided to assist the user in proper selection of the cable.**

NOMENCLATURE

A	17.0
A_c	cross sectional area of copper in a conductor (circular mil) (see Table I)
B	3.6
C	0.029
d	diameter of conductor (inches) (see Table I)
D_{ar}	diameter over the armor (inches) NOTE: round and flat cables use different equations to calculate the D_{ar}
D_{jk}	diameter over the jacket NOTE: round and flat cables use different equations to calculate the D_{jk}
q	thermal resistivity of insulation, constraining coverings, and jacket 500°C cm/Watt
LF	cable lay factor, for round cables = 1.02
R_{dc}	conductor resistance at conductor temperature (ohms per foot)
t_{arm}	thickness of armor (inches)
t_i	insulation thickness (inches) 0.090″ for 5000 volt insulation rating
t_j	jacket thickness (inches) 0.060″ for submersible cable
t_r	restraining covering thickness (inches) 0.010″ for these calculations
T_a	temperature of ambient surroundings (°C)
T_c	temperature of the conductor (°C)
T_m	the mean temperature across the gas area (°C)
T_{zr}	temperature coefficient of zero resistance for copper 10.371 circular mil ohms per foot @20°C
TR_g	thermal resistance of the gas zone between the cable surface and the surrounding casing pipe
TR_i	thermal resistance of the insulation
TR_j	thermal resistance of the jacket.

TABLE I
CONDUCTOR MEASUREMENTS

AWG	Configuration	Circular mil Area	Diameter
#6	solid	26240	0.162″
#4	solid	41740	0.204″
#2	stranded	66360	0.292″
#1	stranded	83690	0.332″
#1/0	stranded	105600	0.373″

INTRODUCTION

THERE ARE THREE IEEE Recommended Practices that cover the specification of electrical submersible pump cables. The Recommended Practices address polypropylene insulated cable, ethylene-propylene insulated cable, and field testing of the cable.

These Recommended Practices have recently undergone a five-year review. In an attempt to provide more accurate data, a number of tests were conducted. The results of these tests were used to develop correlation factors for use in the Neher-McGrath relationship.

AMPACITY CALCULATIONS

The useful working life of any cable is adversely affected by the operating temperature of the cable. Excessive conductor temperature may irreversibly damage the cable insulation and jacket.

Submersible pump cables are applied in harsh environments with high ambient temperatures. The ambient in conjunction with conductor heat rise makes effective application of submersible cable a tedious process. This paper provides the cable user with a method to estimate the maximum conductor temperature for the submersible pump cable application.

The ampacity calculations are developed from the Neher-McGrath formula (see eq. 9 of [1]). Their equations were based on work derived in the early 1930's for high-voltage power cables. Nevertheless, their paper was first presented in 1957 at an IEEE (AIEE) meeting in Montreal, Canada. Their equation for cable ampacity is identified:

$$I = sqrt\left[\{T_c - (T_a + T_d)\}/\{R_{dc} * (1 + Y_c) * TR\}\right] \quad (1)$$

where

I conductor current (amperes)

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T_a	temperature of ambient surrounding cable (°C)
T_c	temperature of conductor (°C)
T_d	temperature rise of conductor due to dielectric loss (°C)
R_{dc}	dc resistance of conductor at conductor operating temperature T_c (ohms per foot)
$1 + Y_c$	ac/dc resistance ratio
TR	thermal resistance (per conductor) between the conductor and ambient (thermal-ohm-foot).

MODIFIED CALCULATIONS

The Neher-McGrath relationships are modified for submersible cable. Some of the calculations will be more complex. However, several assumptions can be made to simplify the ampacity calculations for pump cable applications.

The 600-to-5000-V range used in pump cables allows the removal of the dielectric loss portion of the original equation. The actual dielectric losses are very small. Therefore, the temperature rise due to dielectric T_d may be neglected.

Submersible cable conductors range in size from #6 to #1/0 AWG. For this configuration, the ac/dc ratio is almost equal to one [4]. Thus, the $(1 + Y_c)$ term becomes unity.

For submersible pump cables, the ampacity equation then simplifies as follows:

$$I = sqrt\left[(T_c - T_a)/(R_{dc} * TR)\right]. \tag{2}$$

There are a number of terms and abbreviated symbols used in developing the relationship. The Appendix contains an alphabetic listing of these symbols. Numeric values are given where constant terms are employed.

Each of the terms will be analyzed in detail. The most complex component of the equation is the thermal resistance (TR). This parameter incorporates the physical characteristics of the cable as well as the application configuration.

TEMPERATURE OF CONDUCTOR

Since the surface of the metal conductor will be the hottest spot within the cable, the surface temperature of the conductor must be restricted to protect the insulation and jacket. The maximum rated conductor operating temperature T_c is dependent on the submersible pump cable construction.

Polypropylene (PP) insulated cables have a rated maximum operating conductor temperature of 96°C (205°F) [6].

Ethylene Propylene Diene Monomer (EPDM) is commonly referred to as EPR insulated cable. These designs may operate at much higher temperatures. An accepted maximum rated conductor operating temperature for EPDM insulated and nitrile jacketed cable is 140°C (284°F) [7].

CONDUCTOR RESISTANCE

During the ampacity determinations, conductor resistance is calculated at the maximum conductor temperature. The conductor resistance relationships are based on uncoated copper. It is assumed that the increase in actual resistance due to coating of the conductors is negligible.

For round cables, derivation of the conductor resistance must include corrections for length of wire. The twisting of the cable conductors effectively increases the actual length in the cable. To compensate, the conductor resistance is increased by 2%. This inflation is incorporated into a cable lay factor (LF). The accepted factor for submersible cable is 1.02. The twisting and length increase does not apply to flat cables. Therefore, the lay factor is one.

The modified conductor resistance may be expressed as follows (see eq. 10 and Table I in [1]). The resistance is measured in ohms per foot at the conductor temperature:

$$R_{dc} = \frac{(\mathrm{LF}) * (R_{20} \text{ of Copper}) * (T_{zr} + T_c)}{A_c * (T_{zr} + 20)} \tag{3}$$

$$= \frac{(\mathrm{LF}) * 10.371 * (234.5 + T_c)}{A_c * 254.5} \tag{4}$$

where

LF	cable lay factor
R_{20}	resistivity of copper at 20°C
T_{zr}	temp coefficient of zero resistance for copper 234.5
T_c	conductor temperature (°C)
A_c	cross sectional area of the conductor (circular mils).

AMBIENT TEMPERATURES

The ambient temperature surrounds the cable. The value of the ambient is often assumed to be the static bottom hole temperature. However, in a downhole environment, the ambient temperature depends not only on the bottom hole conditions but on a number of other factors. The temperature gradient from the perforations to the cable, the heat rise from the submersible equipment, and the heat generated from the cable all have an effect on the ambient temperature.

For the ampacity calculations carried out in this project, T_a may vary from 40°C (104°F) to 140°C (284°F).

THERMAL RESISTANCE

For submersible applications, the TR value consists of three parts. These components are the insulation TR_i, jacket TR_j, and the gas zone between the cable and pipe casting TR_g [2].

TR is expressed in thermal-ohm-feet (tof):

$$TR = TR_i + TR_j + TR_g \tag{5}$$

where

TR_i	TR of the insulation
TR_j	TR of the jacket
TR_g	TR of gas zone between the cable surface and surrounding casing pipe.

THERMAL RESISTANCE OF THE GAS ZONE

Cable that is installed within a metal conduit, such as a well casing, has some contact with the metal surface. However, much of the cable is exposed to the gas within the conduit. The heat transfer characteristics of the gas zone dramatically affects the ability of the cable to dispose of heat.

From the original Neher-McGrath paper, an expression for calculating TR_g may be obtained (see eq. 41 of [1]). The units are tof:

$$TR_g = 3 * A / [1 + \{(B + (C * T_m)) * D_{ar}\}] \quad (6)$$

where A, B, and C are constants. The article (see Table VII of [1]) provides numeric values for the A, B, C terms under some conditions. For example, a cable in an air-filled metal conduit has constants $A = 17.0$, $B = 3.6$, and $C = 0.029$. This configuration is most similar to a submersible cable operating above the fluid level of the well.

Mean Temperature

The parameter T_m symbolizes the mean temperature across the gas area. The result is dependent on the temperature of the cable conductor T_c and the ambient temperature T_a.

Many of the values used must be experimentally developed since each application is different. Tests were conducted by placing a thermocouple in the air space. The thermocouple was 1 in from the cable. An experimental factor of 0.3 was necessary to correct the mean temperature parameter. The mean temperature (T_m) is now defined:

$$T_m = T_a + [(T_c - T_a) * 0.3]. \quad (7)$$

Diameter

The parameter D_{ar} depicts the diameter (in inches) over the armor. For PP and EPDM insulated cables, the insulation thickness t_i is set at 0.090 in. This measurement is characteristic of 5000-V rated cables. Calculations made with 0.075-in cable, which is the insulation thickness of 3000-V rated cables, do not appreciably alter the end result.

Typically, submersible pump cable constructions include a constraining covering with a thickness t_r over the insulation. It is assumed that this layer adds another 0.010 in to the insulation wall.

For PP and EPDM insulated round and flat cables, the jacket thickness t_j is set at 0.060 in. The nominal armor strip thickness t_{arm} is 0.025 in for round cables. To compensate for the armor interlocking profile, an additional 0.060 in is included in the summation.

Considering all these components, the diameter over round cable armor D_{ar} may be calculated as follows. The dimensions are in inches:

$$D_{ar} = [d + (2 * t_i) + (2 * t_r)] * 2.155 + (2 * t_j) + (4 * t_{arm}) + 0.060'' \quad (8)$$

where

t_i	insulation thickness
t_r	restraining coverings thickness
t_j	jacket thickness over the insulation
t_{arm}	thickness of armor
d	diameter of conductor.

A different procedure is used to determine the diameter over flat cable armor. Furthermore, there is a difference in the armor thickness. The nominal armor strip thickness t_{arm} diminishes to 0.020 in.

The D_{ar} measurement is taken in the flat direction. This orientation is used since the cable is mounted with the flat side primarily exposed to the gas zone:

$$D_{ar} = [d + (2 * t_i) + (2 * t_r)] + [2 * T_j] + [4 * t_{arm}]. \quad (9)$$

THERMAL RESISTANCE OF THE INSULATION FOR ROUND CABLES

An expression for calculating the thermal resistivity of the insulation TR_i of round cables may be obtained from the Neher-McGrath paper (see eq. 39 of [1]). The reference assumed copper had a constant temperature coefficient. The relationship is modified for variations in the thermal resistivity:

$$TR_i = 0.0052 * q * G_1 * TCF \quad (10)$$

where

q	thermal resistivity of insulation material 500°C cm/W (see Table VI of [1] and see [3])
G_1	geometric factor
TCF	temperature correction factor.

A mathematical formula for calculating the geometric factor is as follows (see [5] and eq. 8 of [1]):

$$G_1 = 2.30 \log_{10} [3 * (G_2 + 1)] \quad (11)$$

$$G_2 = \frac{[(8 * (t_i + t_r)) + t_j] * [t_i + t_r + t_j]}{4 * d * (t_i + t_r)}. \quad (12)$$

A correction factor (TCF) has been developed to compensate for changes in the thermal resistivity with temperature. The factor is a mathematically derived number based on the positioning of the three conductors and the ratios of thickness of the insulation to the diameter of the conductors:

$$TCF = (d * 1000 + T_c) / T_c \quad (13)$$

where d is the diameter of the conductor (in inches), and T_c is the temperature of the conductor (°C).

THERMAL RESISTANCE OF THE JACKET FOR ROUND CABLES

From the original reference, an expression for calculating the thermal resistance of the jacket TR_j for round cables may be obtained (see eq. 40 of [1]). Again, the TCF has been included to compensate for changes in the thermal resistivity with temperature:

$$TR_j = 0.0104 * q * 3 * [t_j / (D_{jk} - t_j)] * TCF \quad (14)$$

where t_j is the jacket thickness over the insulation, and D_{jk} is the diameter of the jacket.

The diameter over the jacket D_{jk} for round cables may be represented by

$$D_{jk} = [d + (2 * t_i) + (2 * t_r)] * 2.155 + [2 * t_j]. \quad (15)$$

THERMAL RESISTANCE OF THE JACKET AND INSULATION FOR FLAT CABLE

The TR_i and TR_j values are different for flat and round cables. Neher and McGrath presented an expression for

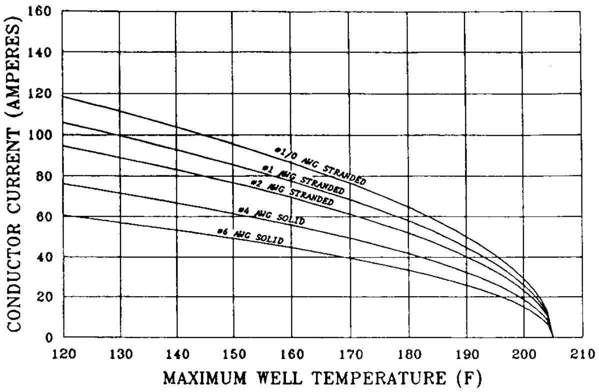

Fig. 1. Ampacity for round cable, polypropylene, 205F conductor.

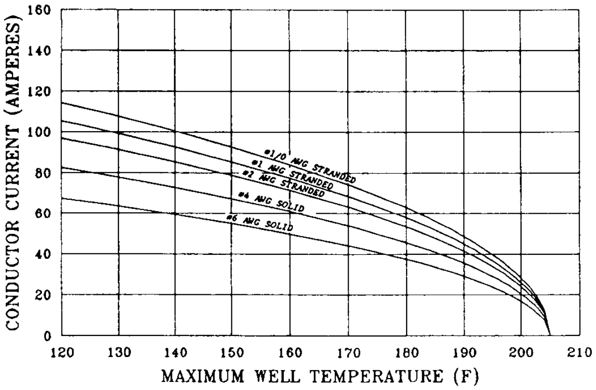

Fig. 2. Ampacity for flat cable polypropylene, 205F conductor.

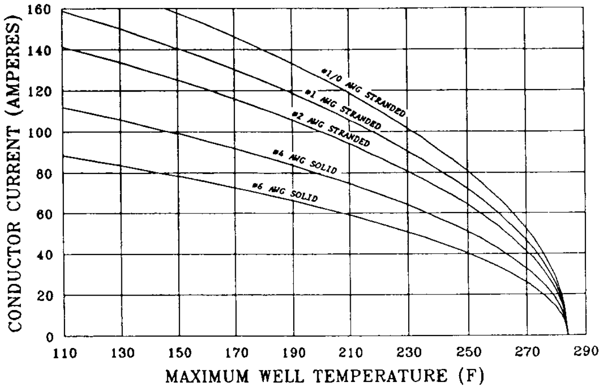

Fig. 3. Ampacity for round cable, EPDM, 284F conductor.

calculating TR_i and TR_j of flat cables. It is assumed that the thermal resistivity of the insulation, jacket, and any reinforcing layers are equal. For flat cables, the thermal resistance of the insulation and jacket (TR_i and TR_j) are lumped together into one equation.

The referenced expression was derived for flat cable configurations used in high-voltage systems. These types of cables are not closely spaced like the three conductors in a flat pump cable. The thermal resistance would be different in the center insulated conductor.

For pump cable calculations, it has traditionally been assumed that thermal resistance for each conductor is equal. However, experimentation has proven that the center conductor does get slightly warmer than the outer two conductors. The thermal resistance (per conductor) of the insulation and the jacket for flat cables may be calculated as follows (see eq. 38 of [1]):

$$TR_i + TR_j = 0.012 * q * \log\left(D_{jk}/d\right) * TCF. \qquad (16)$$

The value of D_{jk} is calculated based on the insulation thickness, the overlying, constraining coverings or braids, and the jacket thickness. For flat cables, the diameter over the jacket D_{jk} may be established:

$$D_{jk} = \left[d + (2 * t_i) + (2 * t_r)\right] + \left[2 * t_j\right]. \qquad (17)$$

AMPACITY CHARTS

Using the derived ampacity equations, a series of ampacity curves may be generated. Four such graphs are displayed.

Figs. 1 and 2 are ampacity charts for round and for flat polypropylene insulated-pump cables, respectively. The plots exhibit the maximum current loading for different conductor sizes. These graphs were derived using a conductor temperature of 205°F. The ampacity curves for round and for flat EPDM-insulated, nitrile rubber-jacketed pump cables are given in Figs. 3 and 4. The charts depict the maximum current loading for different conductor sizes. These plots were derived using a conductor temperature of 284°F.

EXPERIMENTAL

A series of experiments were conducted to verify the applicability of the correlation factors that were applied to the original thermal model developed by Neher and McGrath. These test were conducted with thermocouples applied to conductors and placed in ambient gas. These tests provided the basis for the correction factor.

CONCLUSIONS

The procedures that have been introduced will provide the user with the method to estimate the conductor temperature of a submersible pump cable. Cable life can be extended by

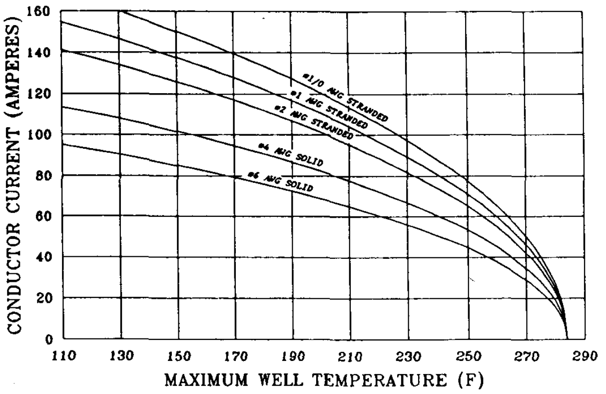

Fig. 4. Ampacity for flat, EPDM, 284F conductor.

not subjecting the materials to thermal abuse. A series of calculations and conversion factors are presented. These modify the Neher-McGrath equations for the unique configuration of electric submersible pump cable.

From the correlations, a series of ampacity charts are arrayed. The curves and equations are a tool for the production or field engineer to assist in the proper selection and operation of an electrical submersible pump system.

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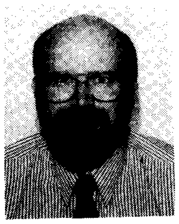

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